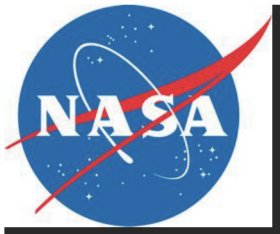
When Did the First Stars Form?



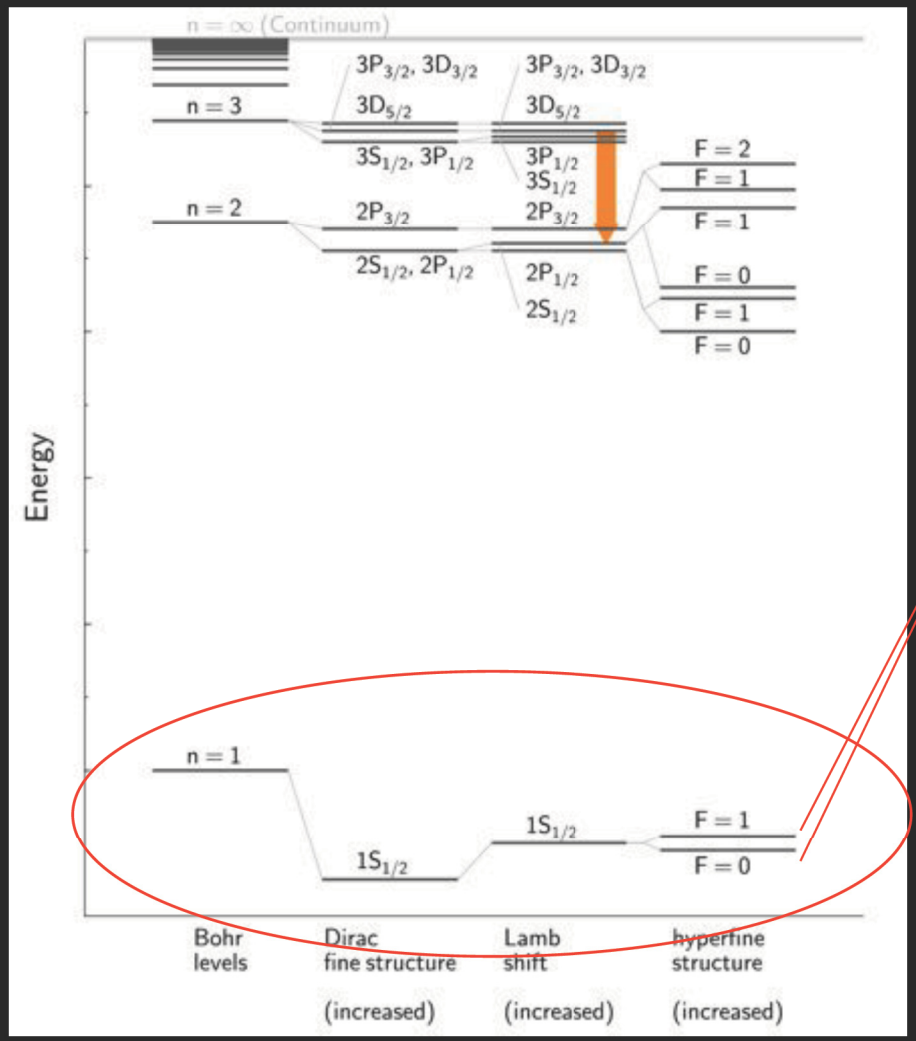
When Did the First Stars Form?

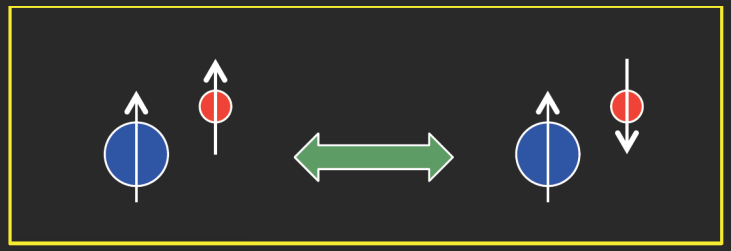
Joseph Lazio*

(Jet Propulsion Laboratory, California Institute of Technology)

* Ph.D. '97

Hydrogen Atom





$n = 1, \mathrm{F} = 1 \rightarrow 0$

$E_{10} = h\nu = 5.8743253\ \mu\mathrm{eV}$

$\mathrm{T}_* = \mathrm{E}_{10}/\mathrm{k} = 0.068\ \mathrm{K}$

$\nu = 1420.405752\ \mathrm{MHz}$

$\lambda = 21\ \mathrm{cm}$

A Brief History of the Universe

370,000 yr ~ 1 billion yr ~ 13.7 billion yr

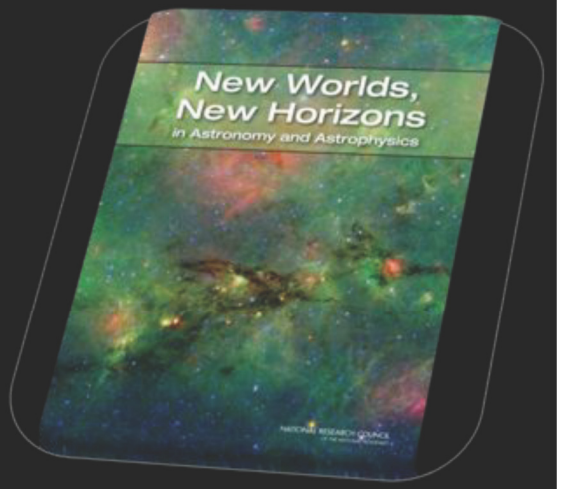
In the past, the Universe was hotter and denser.

Cosmic Dawn and the Dark Ages

"What were the first objects to light up the Universe and when did they do?"

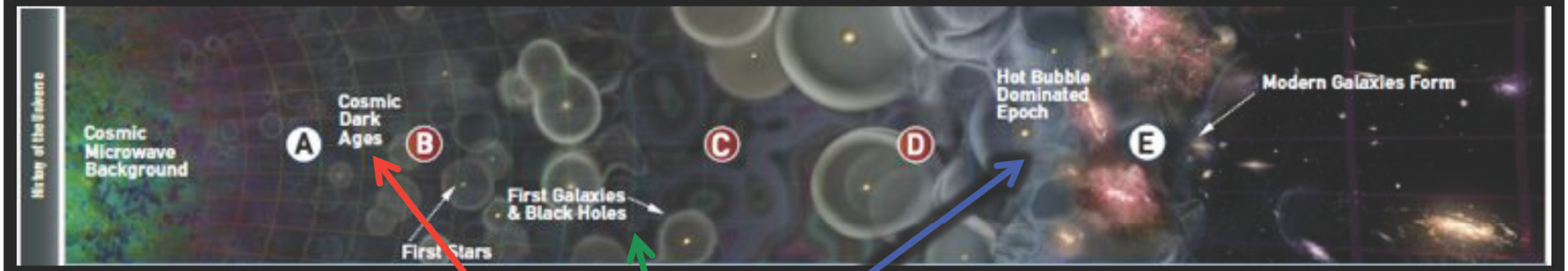
New Worlds, New Horizons in Astronomy & Astrophysics

Cf. European AstroNet



Cosmic Dawn and Dark Ages

Hydrogen Signal



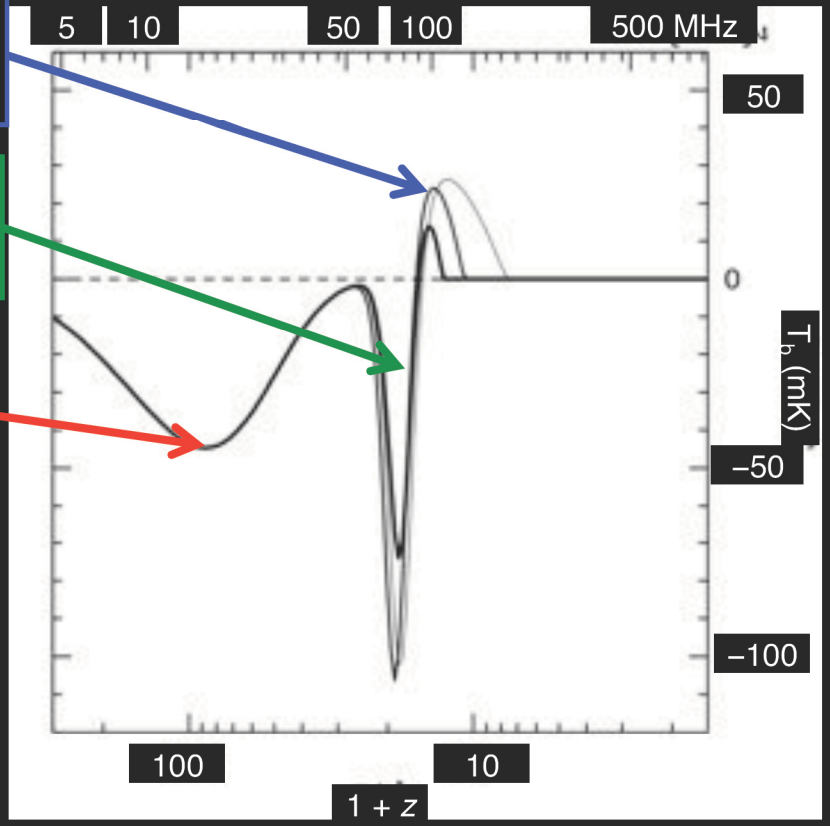
Neutral Hydrogen

Spin-flip transition provides probe of neutral intergalactic medium before and during formation of first stars

EoR

Cosmic Dawn

Dark Ages



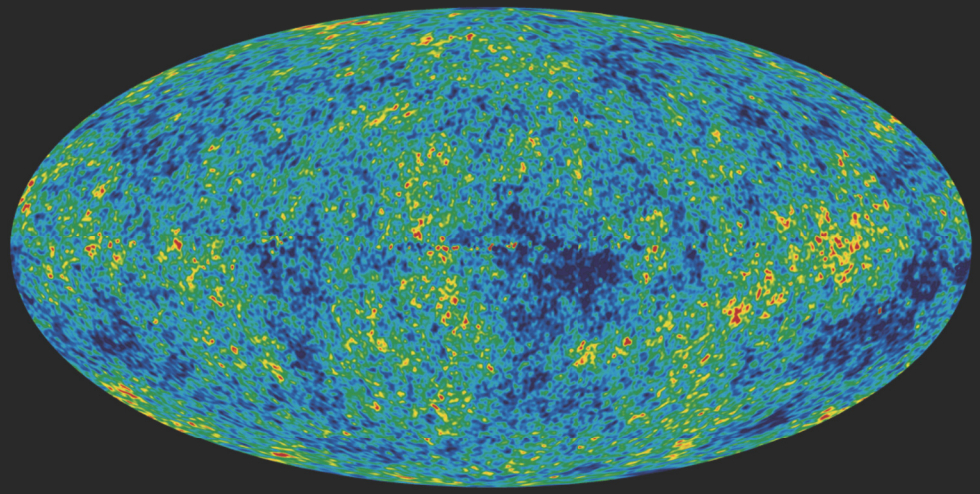
$\nu = 1420 \text{ MHz}/(1 + z)$

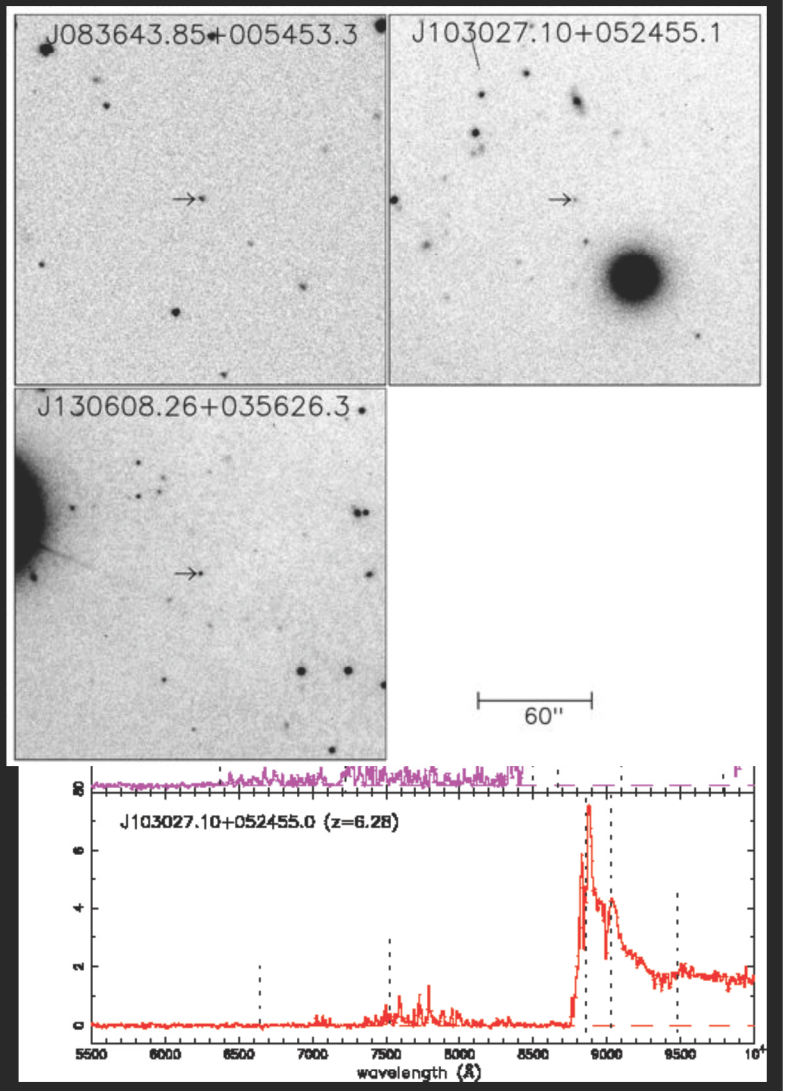
$\lambda = 21 \text{ cm } (1 + z)$

Reionization

Universe made rapid transition from largely neutral to largely ionized

- Gunn-Peterson trough in high-z quasars
- Electron scattering opacity in CMB analysis ($z_{ion} = 10.8 \pm 1.4$)

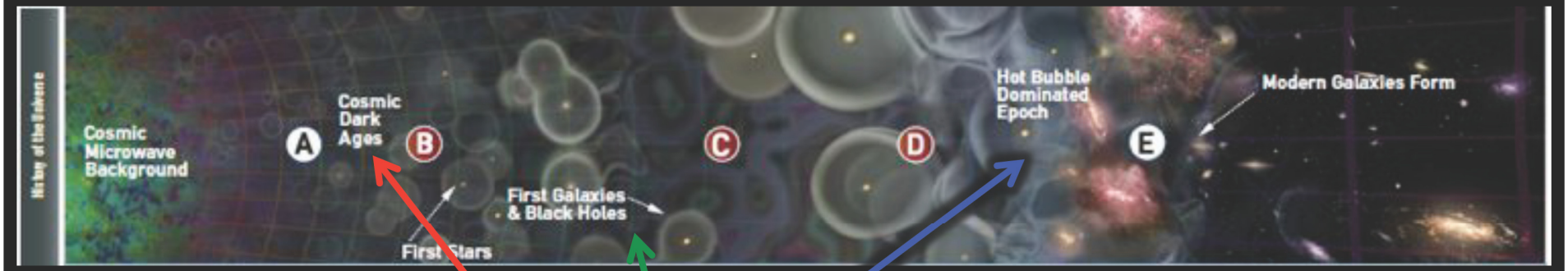




(Fan et al. 2001; Becker et al. 2001)

Cosmic Dawn and Dark Ages

Hydrogen Signal



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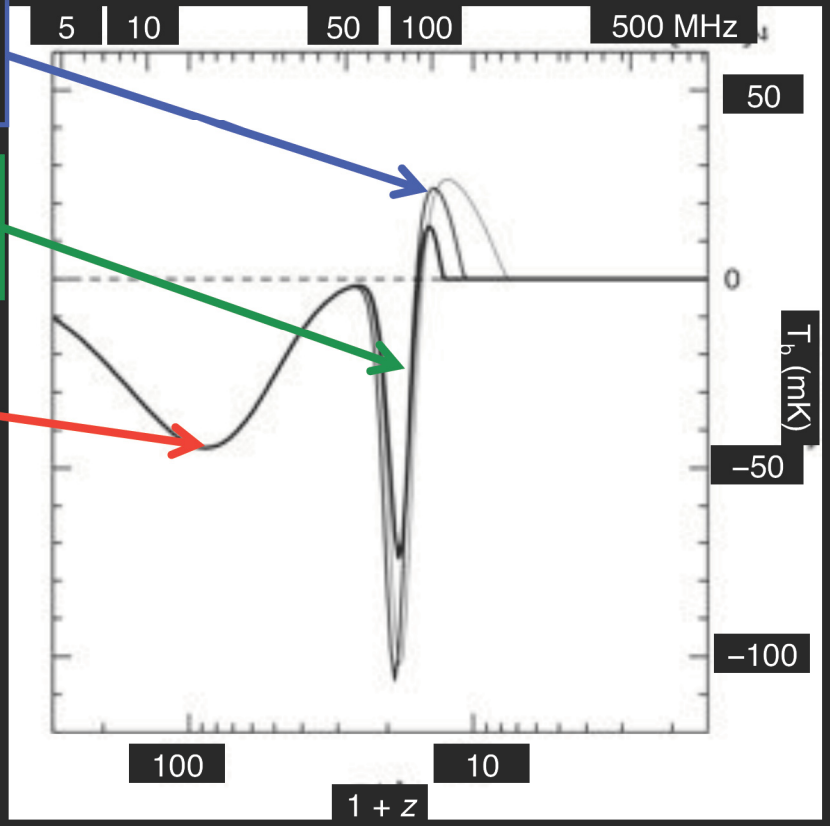

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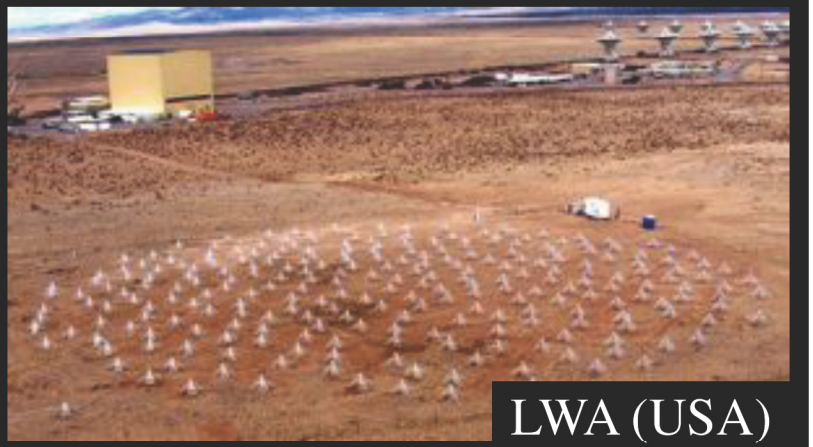
$\lambda = 21 \text{ cm } (1 + z)$

21 cm Cosmology Arrays

LOFAR (Netherlands et al.)

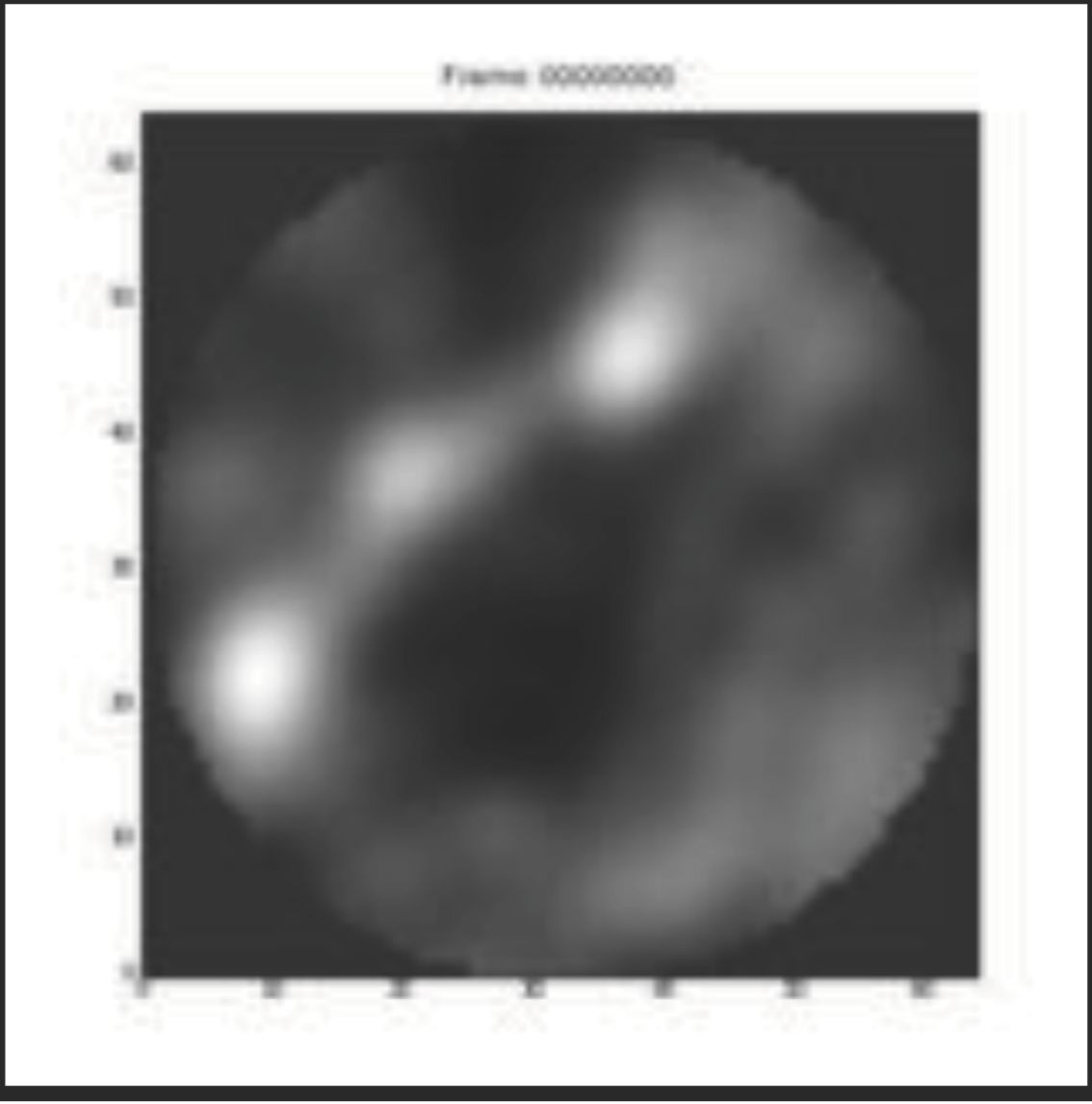


LWA (USA)

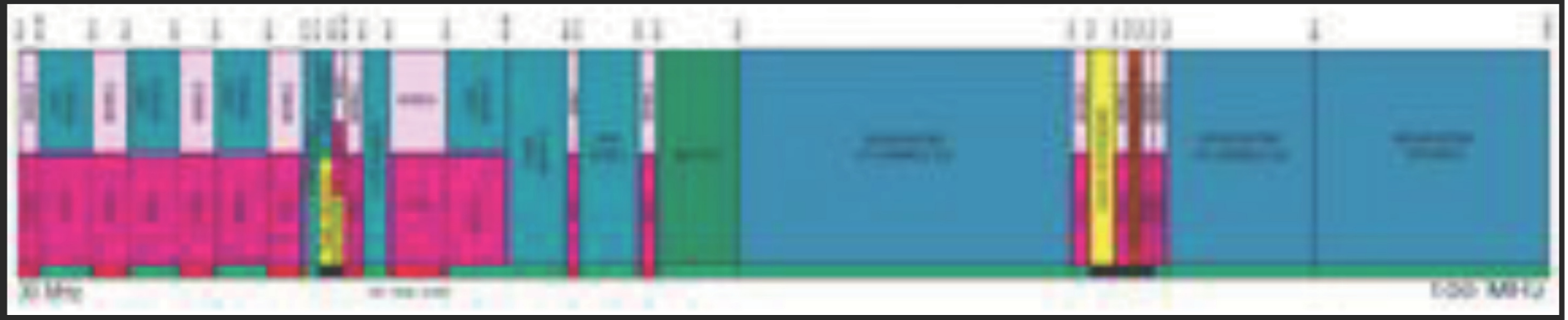
MWA (Australia, India [USA])

PAPER (USA, South Africa)

What's the Problem?



Radio Shielded Zone of Moon



50 Myr since Big Bang

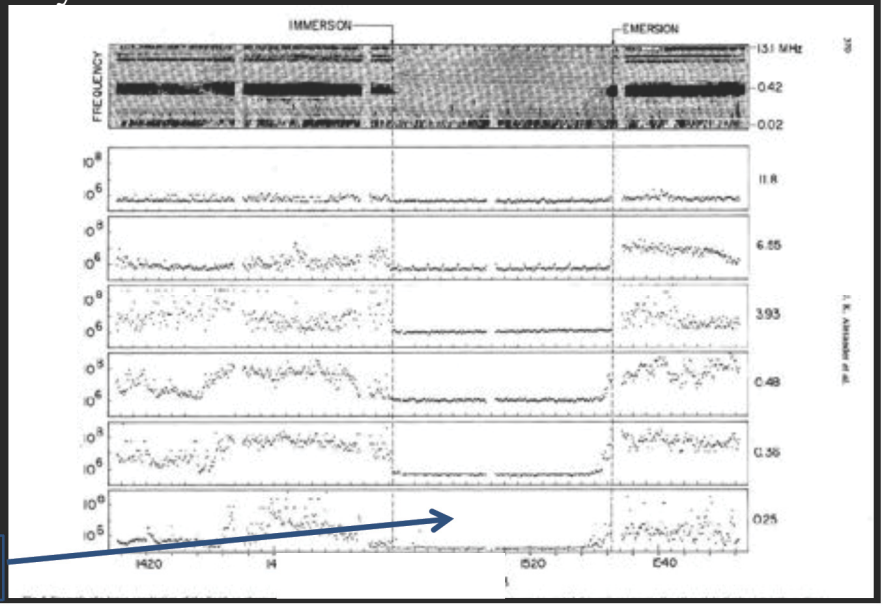
Portion of radio spectrum relevant for 21 cm observations of Cosmic Dawn and Dark Ages

- Yellow = reserved for radio astronomy

330 Myr since Big Bang

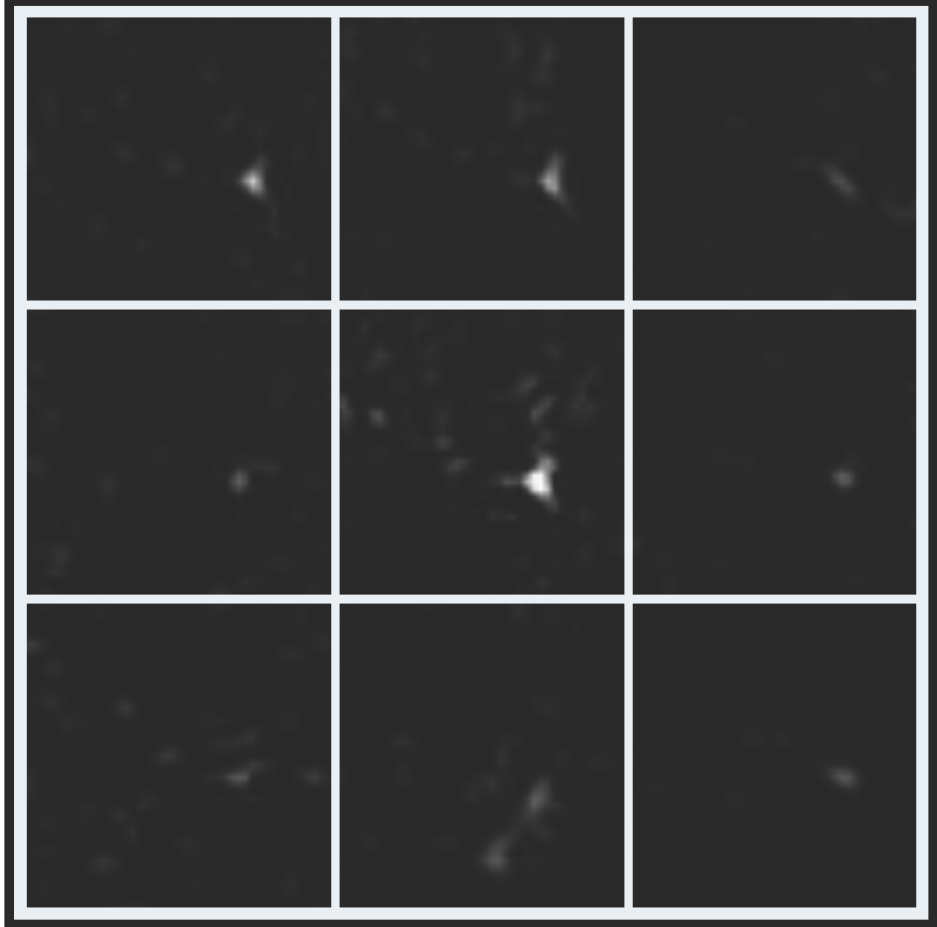
Data from Radio Astronomy Explorer-2, when it passed behind the Moon, illustrating cessation of terrestrial emissions

- *Apollo* command modules lost communications when behind the Moon.



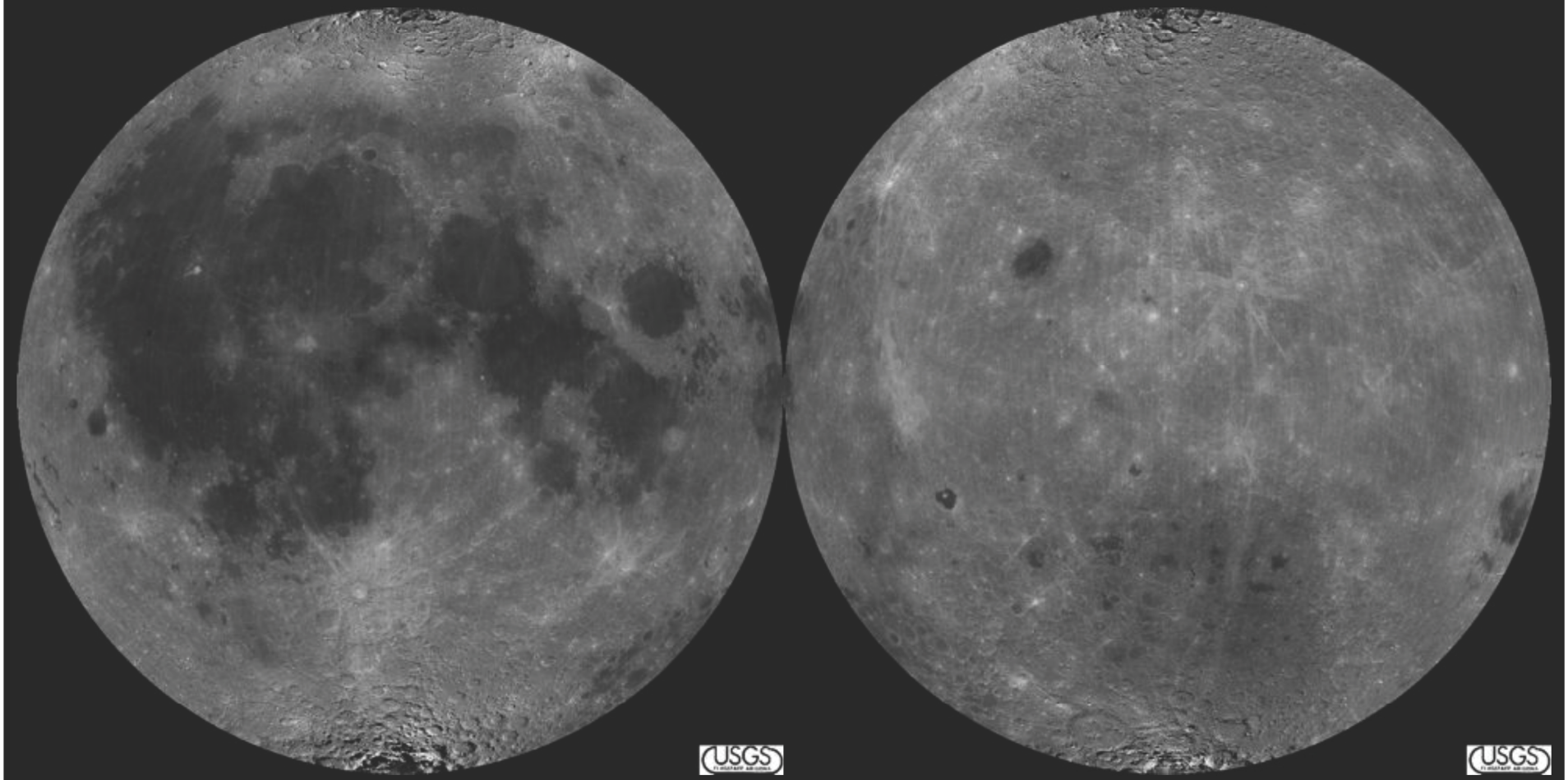
RAE-2 behind Moon

Ionospheric Effects



- Ionosphere significant even at 74 MHz!
  - $z \sim 20$
- Opaque below ~ 10 MHz
  - Actual frequency highly dependent on solar cycle, location, …
  - Increased absorption even as high as 100 MHz
- Moon has no permanent atmosphere/ionosphere

The Moon

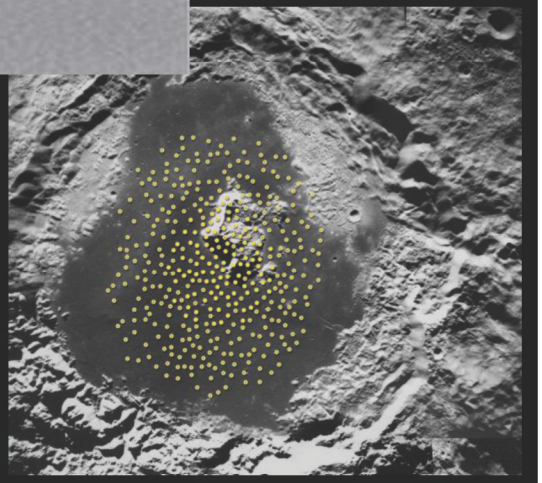


Clementine images of the Moon

Lunar Radio Array

Key subsystems

- Antennas
- Receivers/beamformers
  - long heritage of HF/VHF receivers
- Rover deploys a station/set of antennas
- Data storage
  - ~ 500 Tb per lunar night
- Data transmission
  - Lunar laser links
- Correlator
  - Hundreds of stations
  - *Small* bandwidth (~ MHz)
- Relay satellite downlink
- Ground operations station



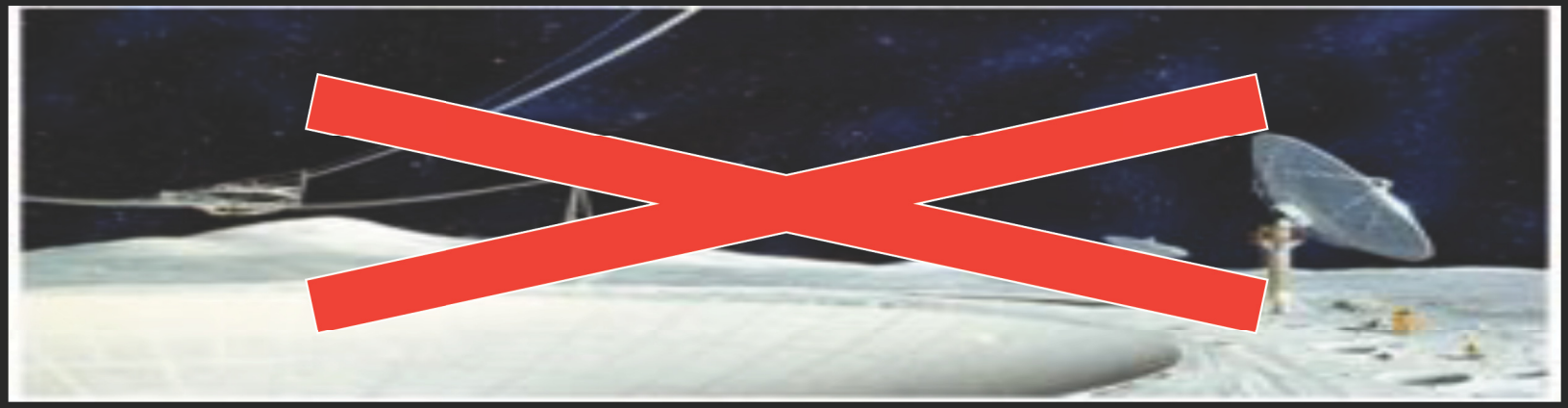
Lunar Radio Telescope

LUNAR
LUNAR UNIVERSITY NETWORK for ASTROPHYSICS RESEARCH

Not a new idea!

- First proposals *pre-date* Apollo missions
  - Research Program on Radio Astronomy and Plasma for Apollo Applications Program Lunar Surface Missions: Final Report 1966, North American Aviation Inc.
  - Greiner, J. M. 1967, "Utilization of Crater Reflectors for Lunar Radio Astronomy," Working Group on Extraterrestrial Resources
- Far side of Moon long recognized as unique astronomical platform

  International Telecommunications Union radio quiet zone



Antennas

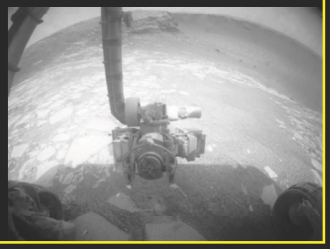
- Antennas deposited on polyimide film.
- Polyimide film has long history of spacecraft applications.

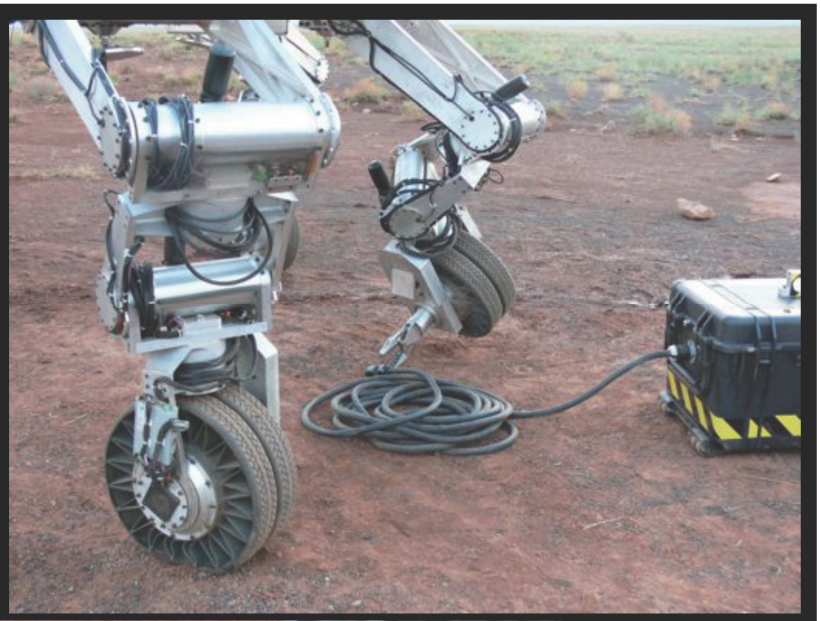
On-going work to test polyimide film antenna electrical properties and in lunar conditions.

Rovers

- Rovers unroll polyimide film rolls containing antennas
  - … might also be able to be used as electronic hubs
- Significant rover heritage

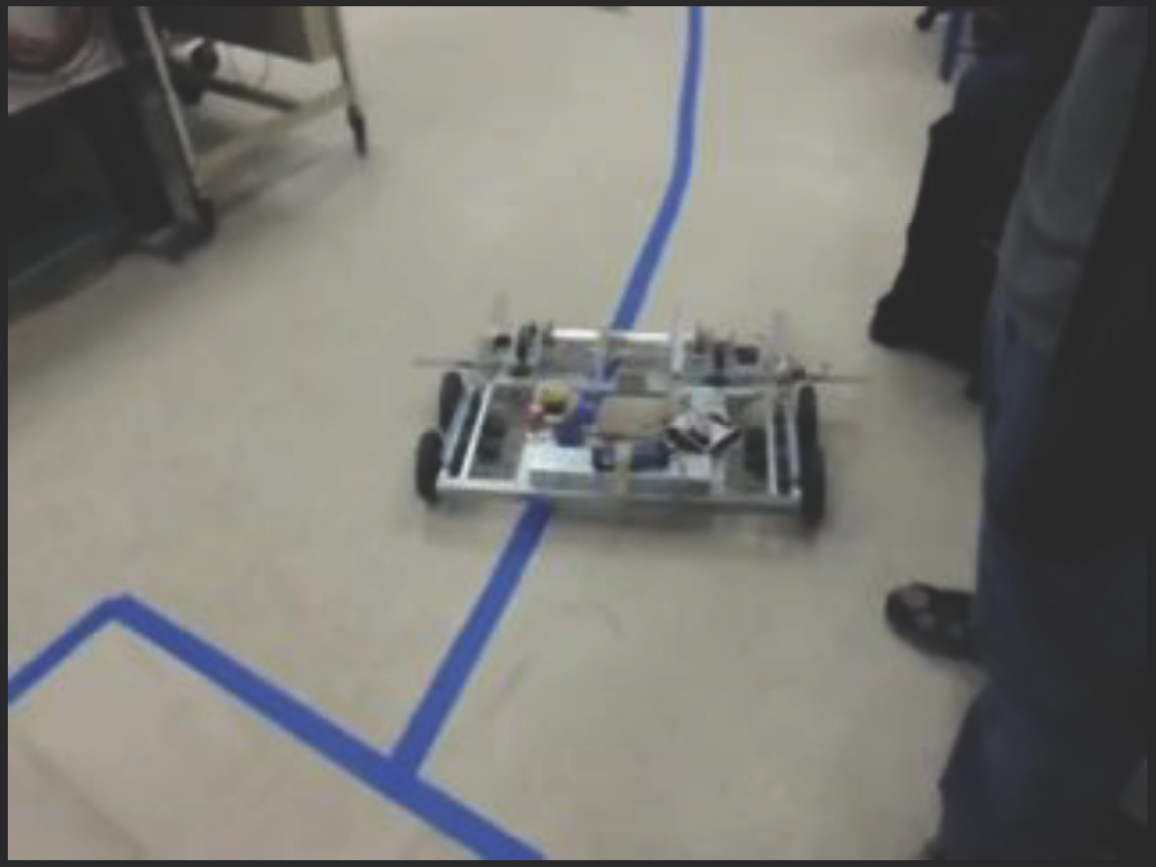
Opportunity @ Mars

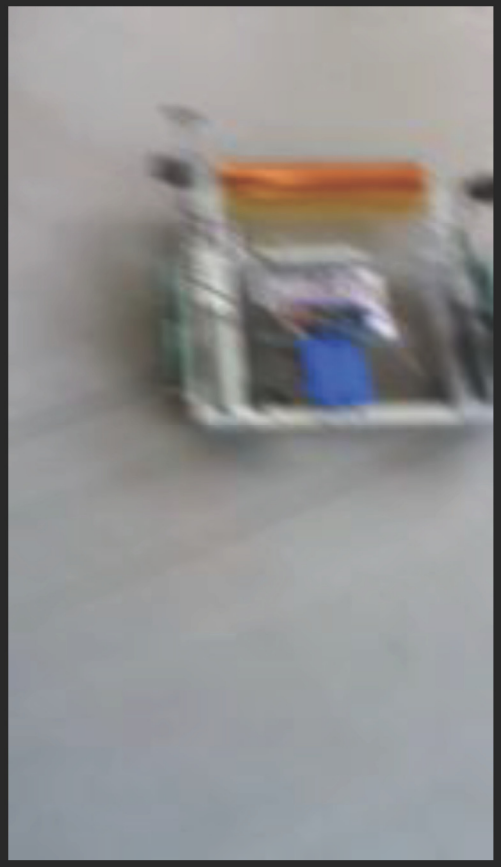




JPL ATHLETE rover

Rovers





So simple, even high school students can do it …!

Thomas Jefferson High School for Science & Technology

H I Cosmology Roadmap

I. 1 (or few) antennas

a. Orbiting Moon, for cosmology

b. On Moon near side, for lunar ionosphere monitoring

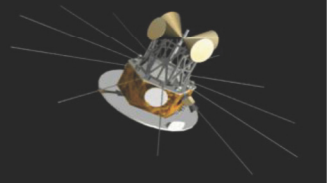
c. On Moon far side, for cosmology

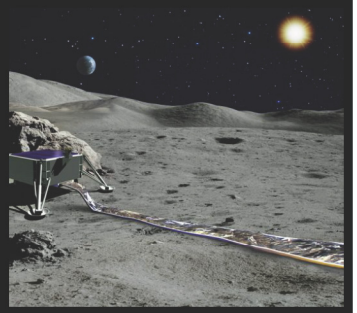
II. ~ 100 antennas

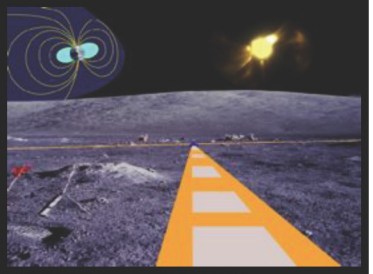
a. On near side, for solar and heliophysics studies

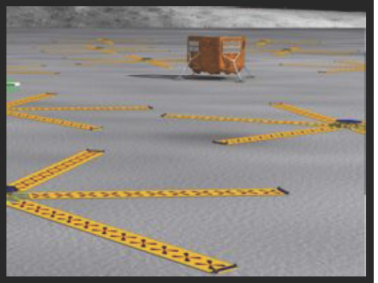
b. On far side, for cosmology

III. > 10^4 antennas, on far side, for cosmology

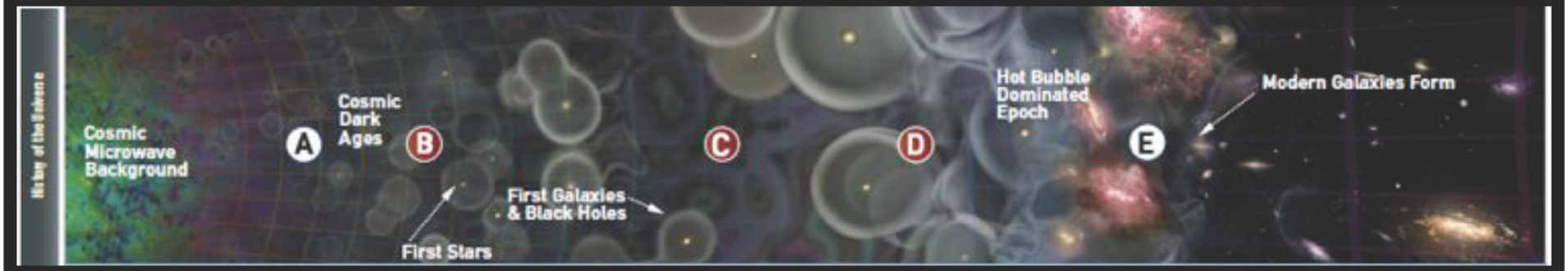


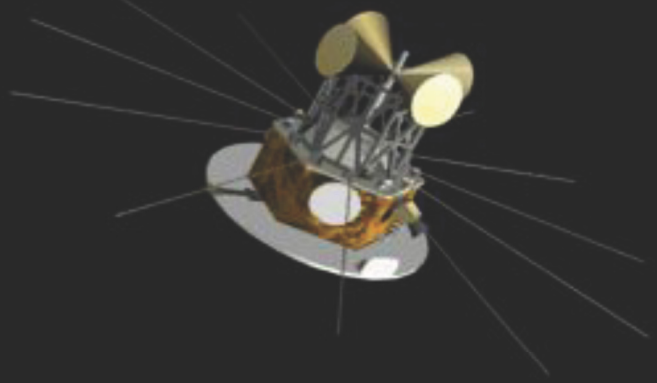


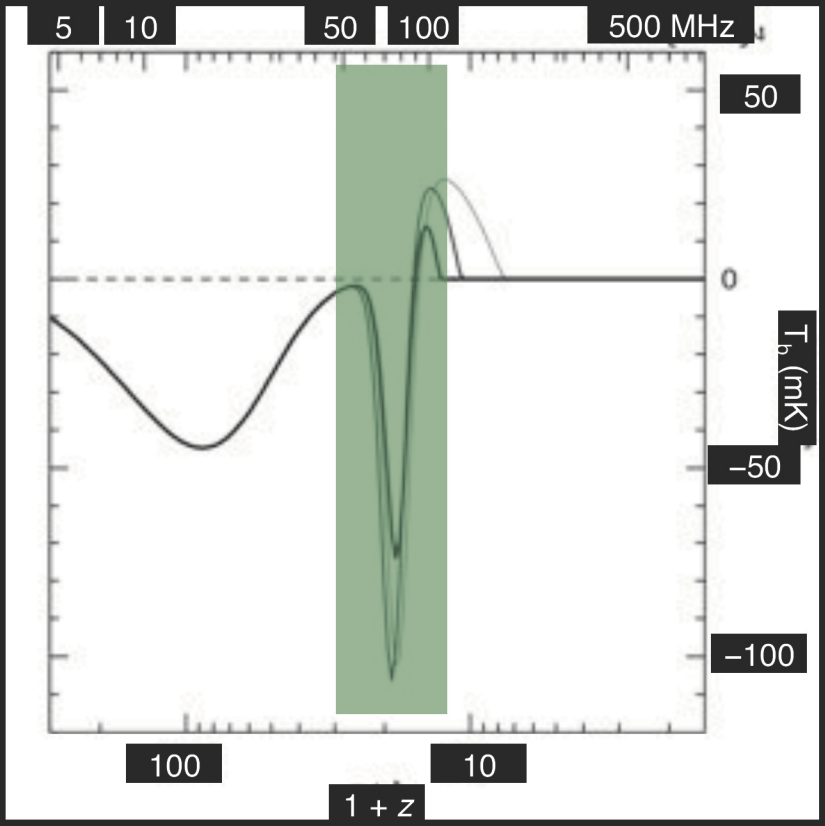




Dark Ages Radio Explorer



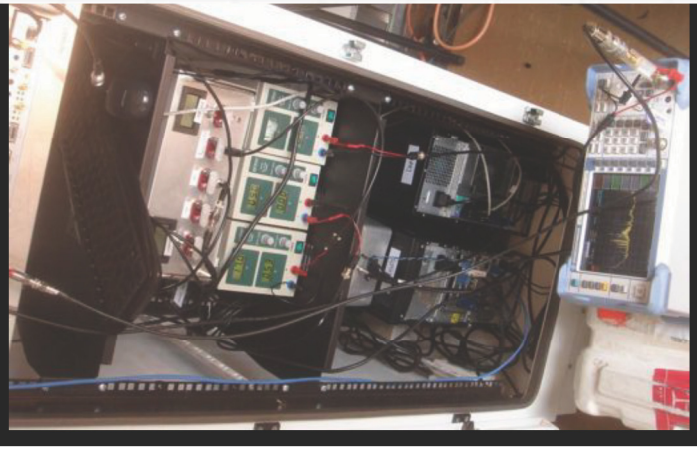




Dark Ages Radio Explorer

DARE prototype antenna in Western Australia

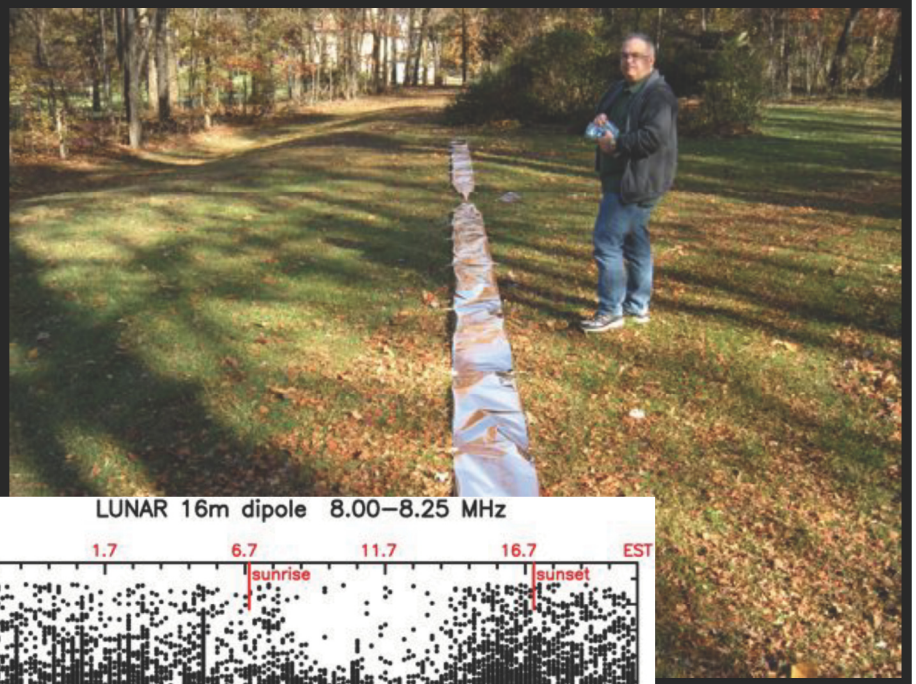
DARE prototype antenna testing in Greenbank, WV

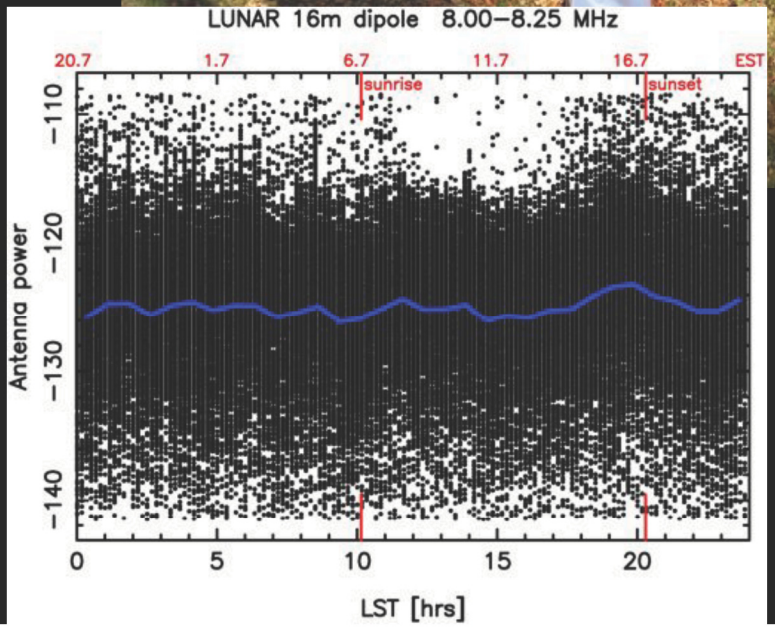


Lunar Atmosphere Probe Station

Moon has tenuous atmosphere

- Can use surface antenna to monitor its properties
- Relative ionospheric opacity measurements

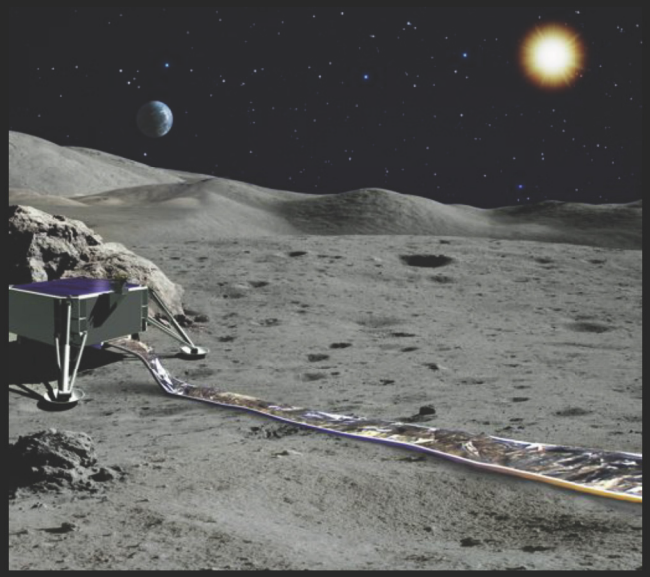


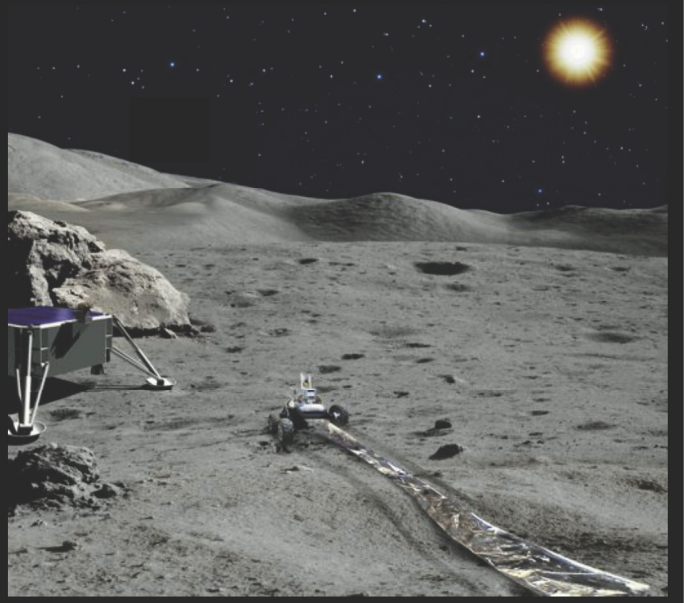


terrestrial ionospheric absroption

Innovative Approaches to the Lunar Surface?

LUNAR
LUNAR UNIVERSITY NETWORK for ASTROPHYSICS RESEARCH

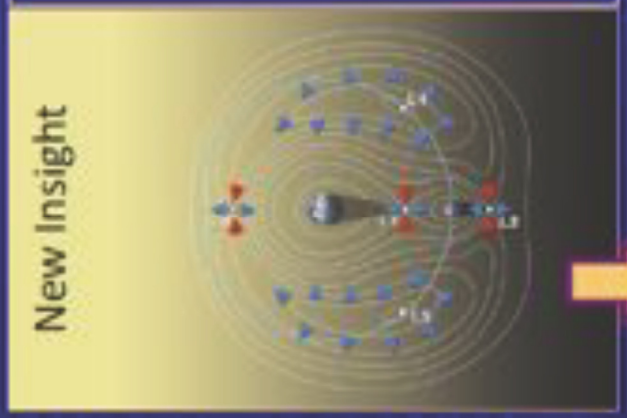




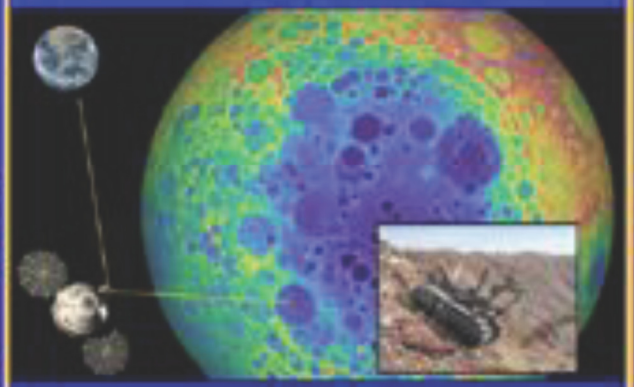
A Farside View: Earth-Moon L2 Lunar Science, Exploration, & Technology Development Concept Mission Study

Going beyond existing LEO capability and experience

Utilize Orion at E-M L2 to develop long duration and tele-robotic capabilities



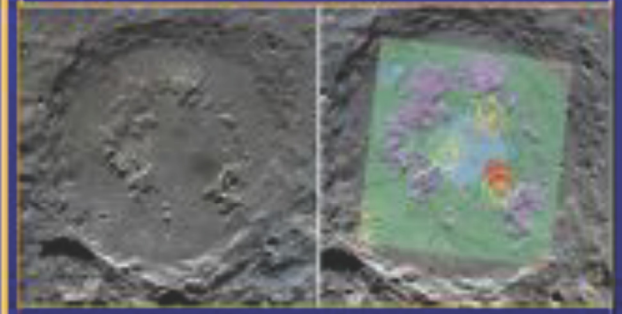
- Develop scientifically-credible lunar farside landing site and surface activities, evaluate data requirements, develop operational protocol



- Critically evaluate the concept mission's support of technology, exploration, and science guiding documents (e.g., those from the NRC)

Integrate human & robotic systems while reducing future mission risk

Provide mission concept that meets science, exploration, & technology development objectives



End-of-Phase Goal

PI Dr. David A. Kring (USRA-LPI), Co-I Dr. Jack Burns (U Colorado)

2/2012

Seeing the First Stars from the Moon

- Exciting science!
  - Best (and only?) way to understand the formation of the first stars
- Moon's far side is an important natural resource
- Roadmap to the future, with important steps this decade